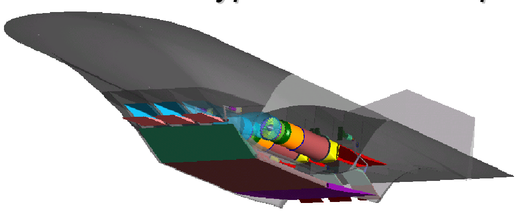
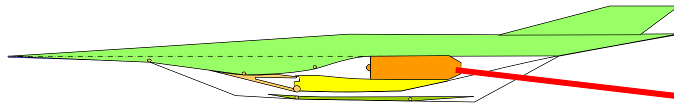
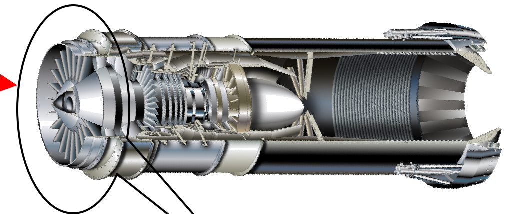
TBCC Fan Stage Operability and Performance

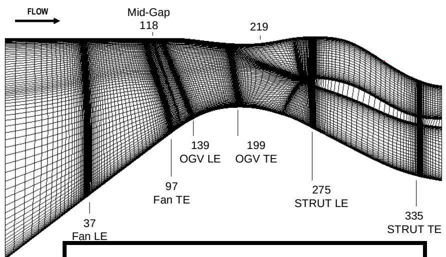
Hypersonic TBCC propulsion - Over /under Configuration



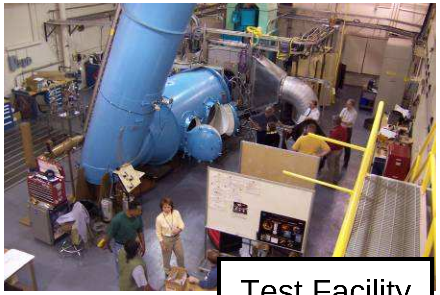


Turbine Based propulsion
Mach 0-4+





CFD GRID (356 x 85 x 55)



Test Facility

NASA Fundamental Aeronautics Program
2007 Annual Meeting

October 31st 2007

Dr. Kenneth L. Suder

API Propulsion Technology Integration
Hypersonics Project

216-433-5899
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Fan Rotor Blisk

Outlet Guide Vane

ACKNOWLEDGEMENTS

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Mechanical Design & Aeromechanics Analysis

- Mark Mielke, GE
- Doug Washburn, GE
- Scott Thorp, NASA
- John Jones, NASA Contractor
- Greg Lung, NASA Contractor

Aerodynamic Design & Aerodynamics Analysis

- Peter Wood, GE
- Dave Clark, GE
- Hyoun-Woo Shin, GE
- Sue Prahst, NASA Contractor
- Aamir Shabbir, Univ of Toledo
- Ken Suder, NASA

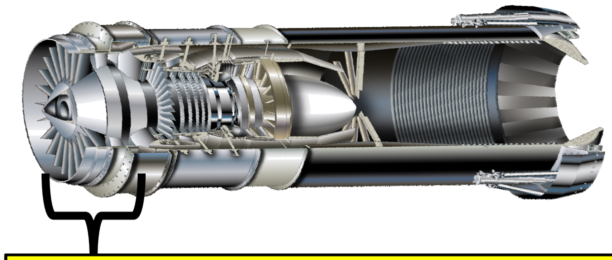
W8 Facility Installation & Operation

- Tom Jett, NASA
- Rick Brokopp, NASA
- Ashlie Flegel, NASA Contractor
- John Dearmon, NASA Contractor
- Helmi-Abulaban, NASA Contractor
- Bruce Wright, NASA

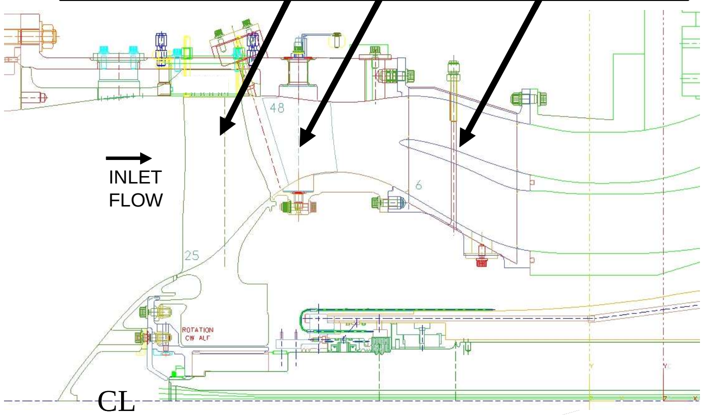
TBCC Fan Stage Operability and Performance

- **Background**
  - **Relevancy /Benefits of TBCC Propulsion**
  - ***TBCC Fan Technology Challenges***
  - ***Overview of NASA TBCC Plan***
- **Objectives / Approach**
- **Fan Stage Design**
- **Test Facility / Instrumentation**
- **Results**
  - **Aeromechanic Checkout**
  - **Overall Performance and Comparison w/ CFD**
  - **Sampling of Data**
- **Summary / Concluding Remarks**

NASA Mach 4+ Capable TBCC Engine Concept



FAN STAGE = Rotor + OGV + Fan Frame Strut



Fan Rotor Blisk

Outlet Guide Vane

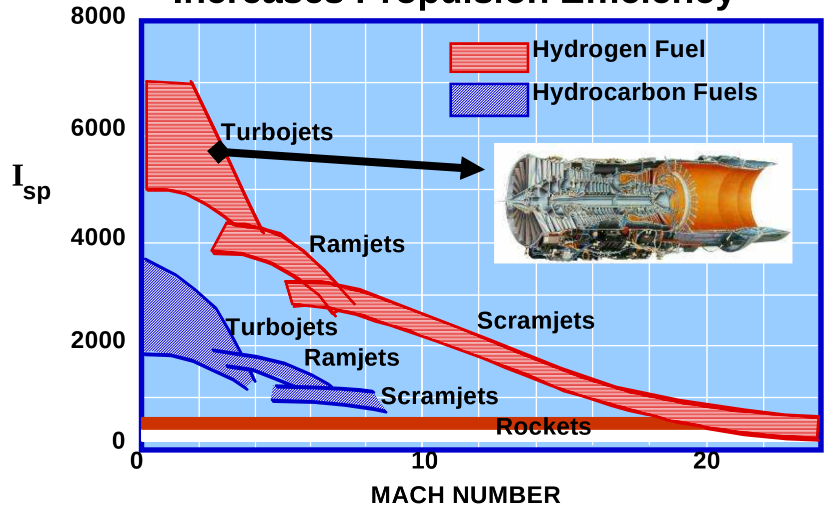
TBCC Propulsion Benefits : Efficiency, Safety, Reliability

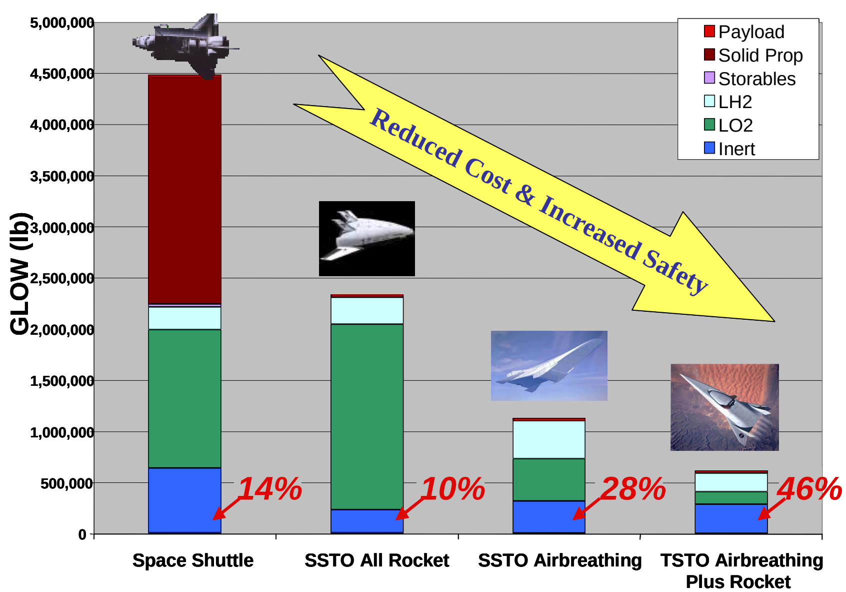
- High effective specific impulse, I_{eff}
- Horizontal takeoff and landing enhances launch, flight and ground operability
  - ✓ Benign ascent abort/engine out
- Large structural mass fraction providing large margins
  - ✓ Design for life
  - ✓ Design for safety
- Reduced sensitivity to weight growth
  - ✓ Reduced design/development risk
  - ✓ Reduced user constraints
- High payload fraction

TBCC BENEFITS:
- Quick Turn Around Time (Aircraft Like Operations)
- Re- useable > 1000 missions
- Versatile Usage + Launch & Landing Sites
- Low Maintenance, High Durability, Performance Margin

I_{SP} = Thrust/Pound per second of propellant (fuel) flow rate

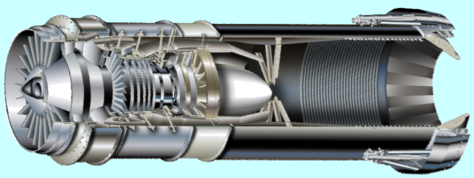
Airbreathing Propulsion Significantly Increases Propulsion Efficiency

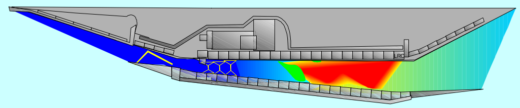


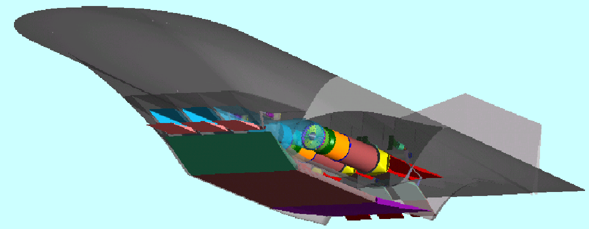


Two Enabling Technologies for Reusable Hypersonic Applications

Turbine Based propulsion + *Hypersonic Scramjet propulsion* → *Hypersonic TBCC propulsion*







High Mach Turbine Tech Challenges:

- Increase Maximum Mach from 2+ ➔ 4+
- Provide thrust margin over entire range (0<M<4+)
  - *Light Weight High Temperature Materials*
  - *Thermal Management*
  - *High Temperature Bearings and Seals*
  - *Highly Loaded Turbomachinery*
  - *Propulsion/Airframe Integration*
  - *Cocooning and Relight*

Scramjet Tech Challenges:

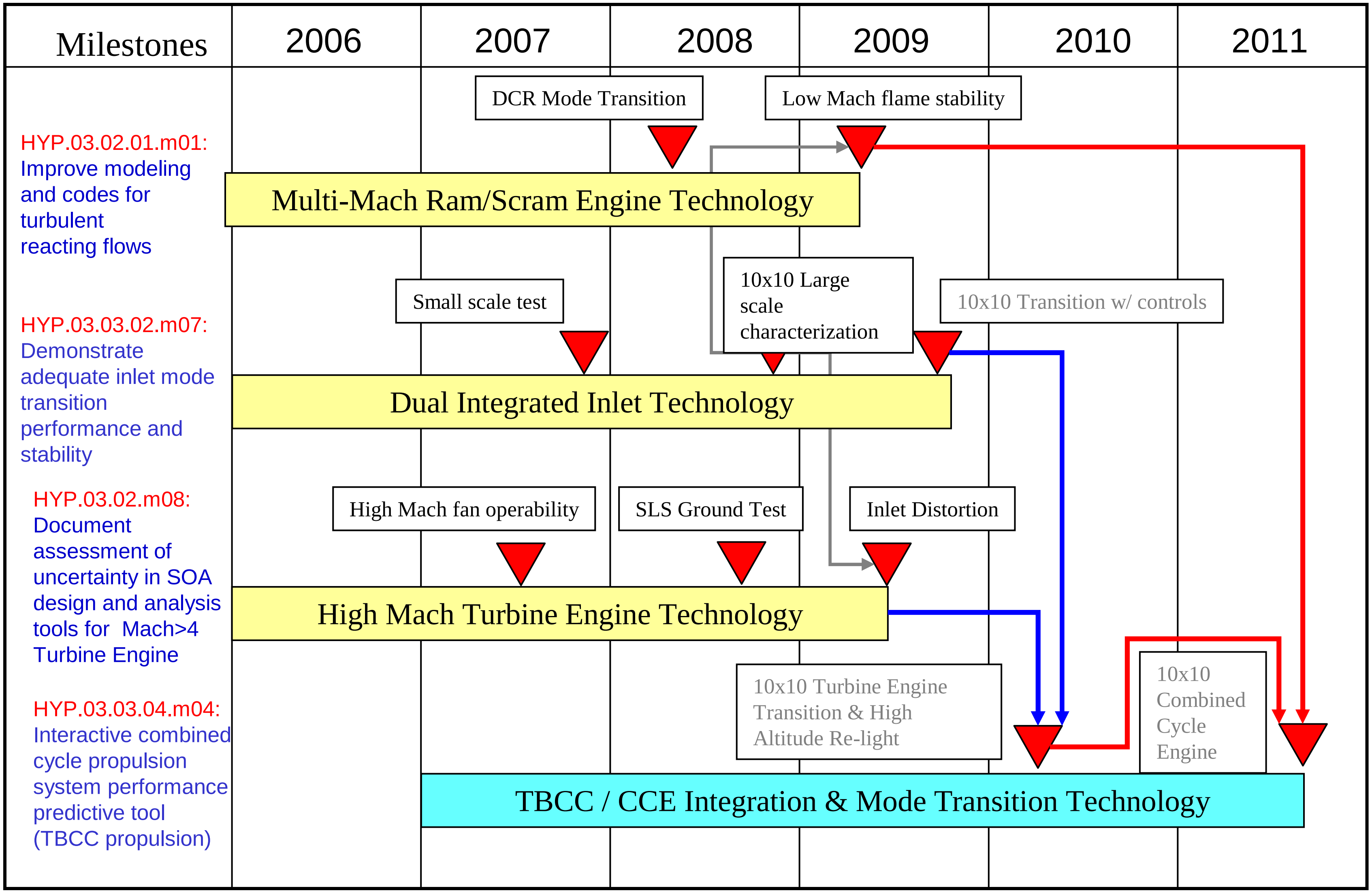
- Reduce Scramjet Ignition Mach Speed (M5 ➔ M3)
- Provide transition speed margin (3<M<4)
  - *Variable Geometry*
  - *Advanced Combustion Schemes*
  - *Light Weight High Temperature Materials*
  - *Thermal Management*
  - *High Temperature Seals*
  - *Propulsion/Airframe Integration*

Required TURBINE Improvements over SOA:

- ✓ **2-3X Thrust / Weight**
- ✓ **4-8X Durability – MTBO**
- ✓ **20-25% Reduction in Fuel Burn**
- ✓ **Increased Mach Capability**
- ✓ **Improved Range**
- ✓ **Conventional Fuel / Lubricants**

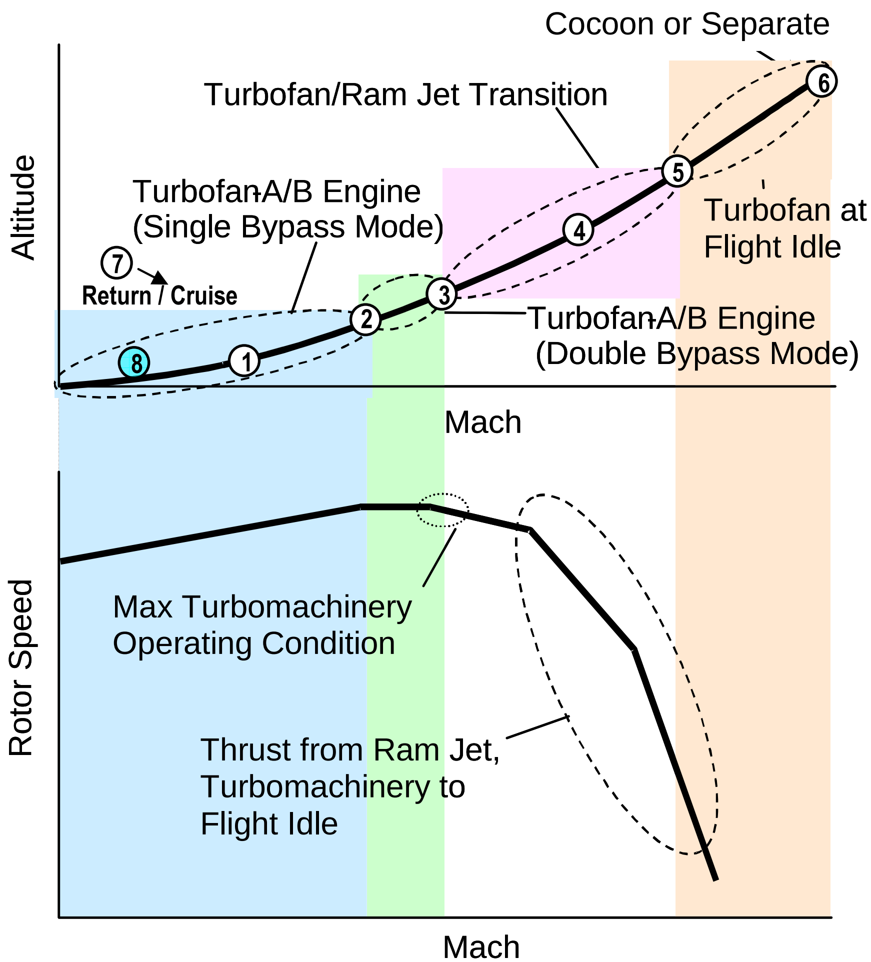
Turbine Based Combined Cycle Engine (CCE)

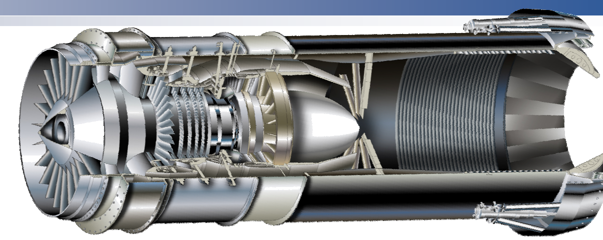
FAP 2007-11 Propulsion Roadmap - Integrates In-House / OGA's / NRA's



TBCC Fan Stage is Integral to CCE effort and is used to assess impact of TBCC inlet distortion on fan stage performance and operability.

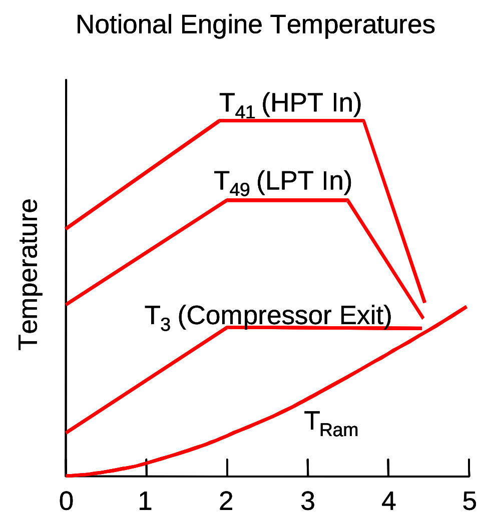
Mach 4 + Capable Variable Cycle Engine Operation





Variable Cycle Engine maximizes thrust over broad operating range:

- Conventional turbojet at low BPR, low Mach
- Converts to Ram burner at high BPR, high Mach
- Enables Mach 4+ using existing materials



High Mach Turbine Engines Challenges Augmented by Wider Operating Range and excess Temperatures relative to SOA Engines

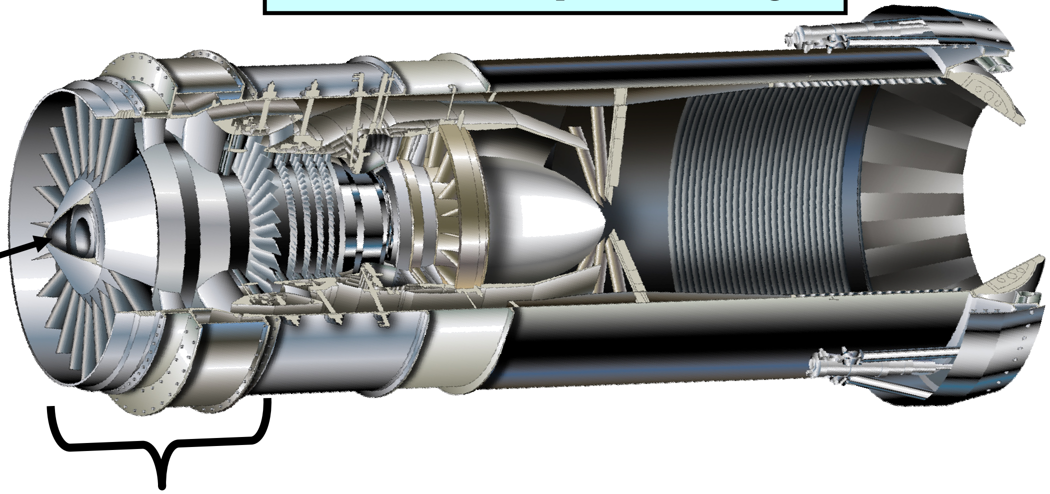
TBCC Fan Stage Operability and Performance

<u>Objective of Fan Stage Research:</u>

Verify SOA design and analysis tools. Characterize a TBCC engine fan stage aerodynamic and aeromechanic performance and stability limits over a wide operating range including power-on and hypersonic-unique windmill operation.

Fan Blisk - ***PR Exceeds SOA***

NASA Mach 4 + capable TBCC engine



Fan Section

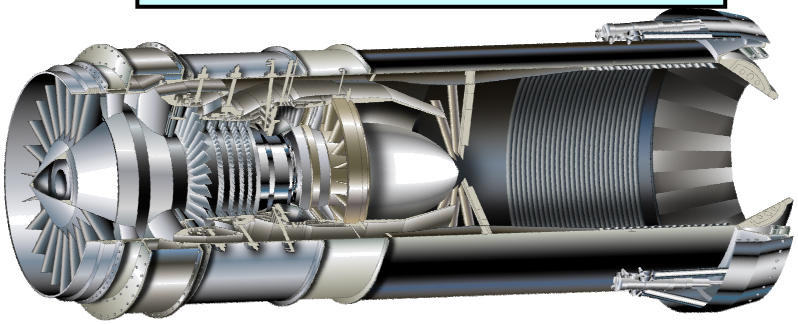
SOA Design & Analysis Tools used to Enable SLS to Mach 4 Range of Operation
(10x variation in bypass ratio, full power to windmill operation,
variations: 8x in rotor speed, 8x inlet pressure, 3x inlet temperature)

TBCC Fan Stage Operability and Performance

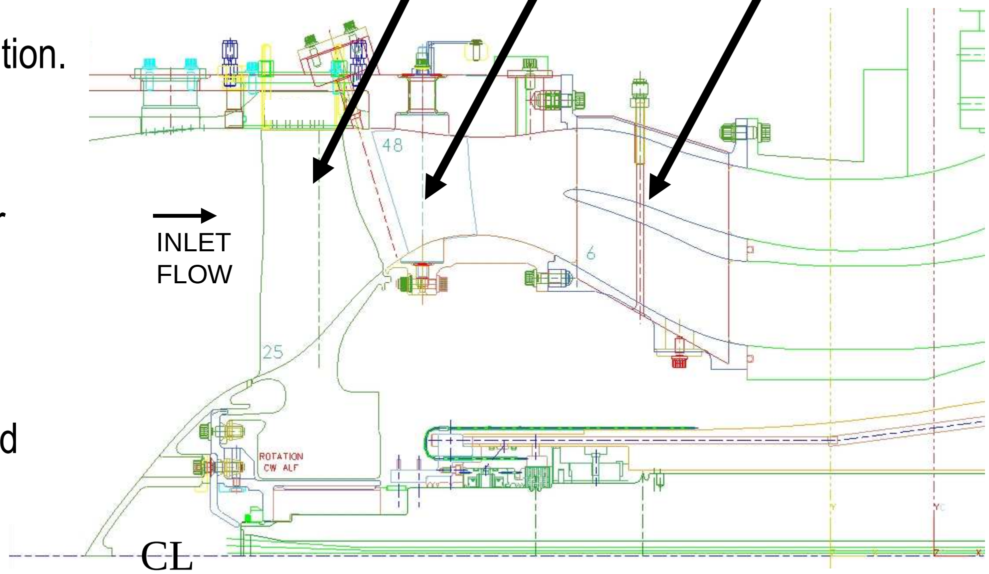
Approach:

- Perform aerodynamic and aero-mechanical scaling of a relevant SOA Mach 4 turbine engine fan stage and incorporate facility interface hardware for sub-scale testing in the NASA high speed compressor facility.
- Predict performance and operability prior to test using SOA analysis tools.
- Map fan stage performance and measure stall line stability boundary over wide range of engine operation and compare to pre-test predictions.
- Measure Fan Aeromechanics: identify vibration and flutter boundaries that adversely impact engine operation. Assess ability of SOA tools to predict flutter.
- Investigate inlet / engine interactions by incorporating inlet distortions and quantify the SOA tool(s) and their ability to predict performance and operability (with distorted inlet inflow).
- Utilize test article to understand physics and improve models required to predict off-design performance and operability

NASA Mach 4 + capable TBCC Engine



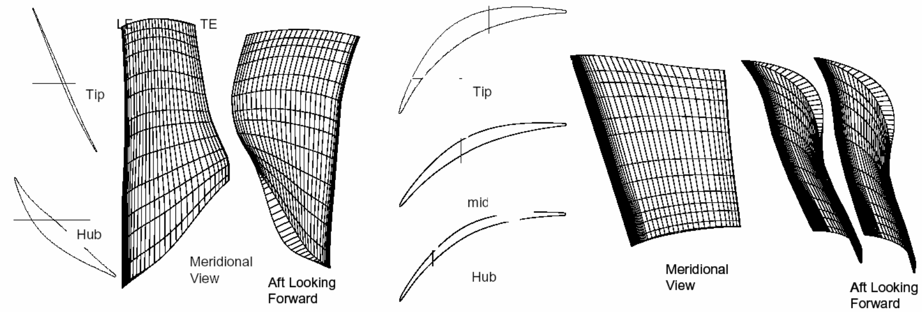
FAN STAGE = Rotor + OGV + Fan Frame Strut



Fan Stage Design

Fan Stage Design Parameters

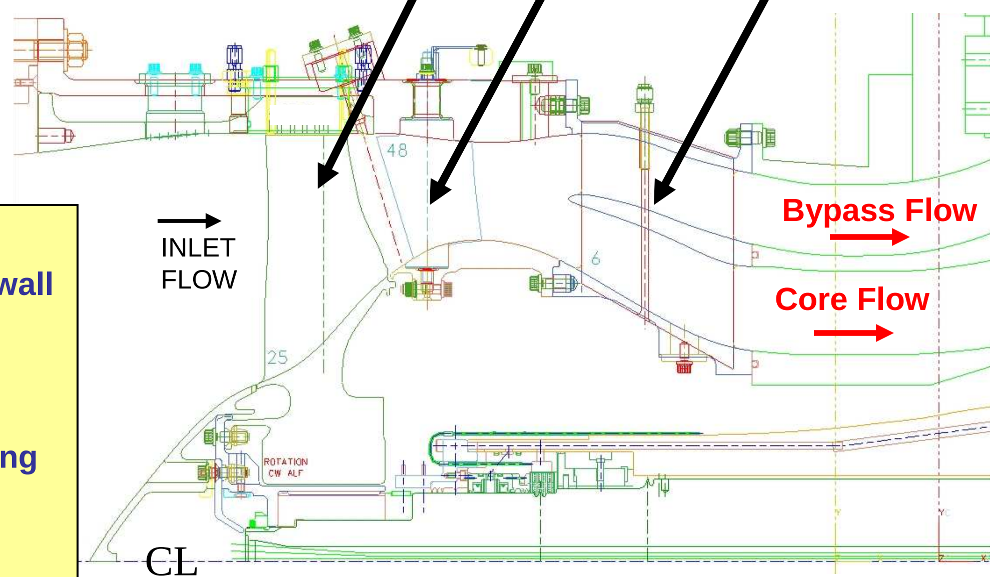
Fan Rotor Tip Speed	1660 ft/s
Fan Rotor Design Speed	17280 RPM
Radius Ratio at LE	0.43
Average Aspect Ratio	1.12
Average Solidity	2.2
Specific Flow	38.0
Design Flow Rate	85.2 lbm/s
Stage Pressure Ratio	2.47
Stage Adiabatic Efficiency	0.85
Stall Margin	20%



a) Advanced technology forward swept fan

b) OGV bowed and leaned at the hub to turn air into the core.

Fan Stage = Rotor (25) + OGV (48) + Strut (6)

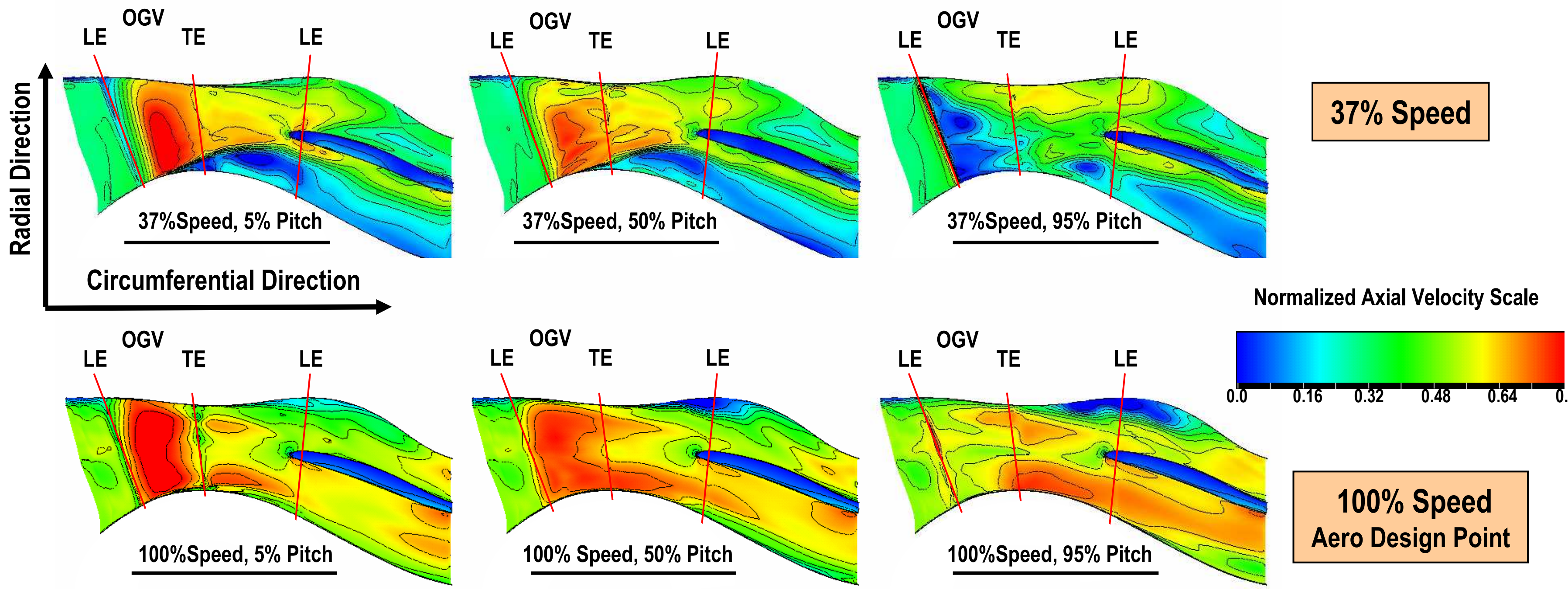


Design Features:

- Liner inserts to evaluate sensitivity to clearance, endwall flow control such as casing treatments.
- Independent throttle valves for bypass and core flow paths to assess sensitivity to bypass ratio.
- Capability to perform parametrics on 1) the OGV setting angle, 2) inlet boundary layer thickness, and 3) inlet distortion.
- Steady state conventional as well as high response instrumentation to assess ability of SOA tools to predict performance and operability.

CFD tools utilized in Fan Stage Design to Accommodate Large Operating Range Requirements

Meridional views of the axial velocity distribution at 5%, 50%, and 95% OGV pitch for the final OGV design.



Final OGV Design Balances Competing Requirements over the Entire Flight Regime

Performance at Take-off

Pass the Flow with minimal losses at High Mach Flight

TBCC High Mach FAN Rig Test - Facility

Mechanical:

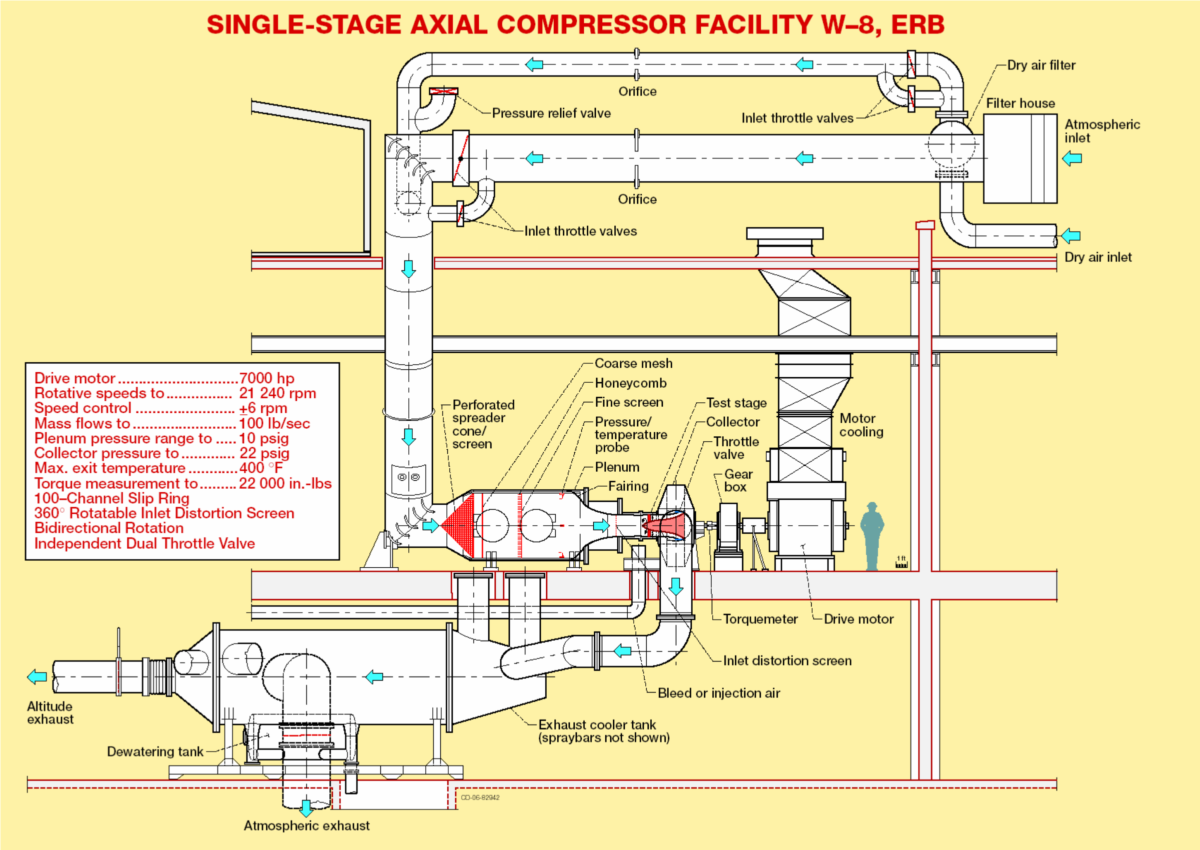
- Shaft power, max: 7000 HP (electric motor)
- Rotational speed, max: 21240 RPM
  - 5.9:1 Gear Ratio
- Approximately 4:1 Pressure Ratio capability
  - Exit temperature limit, 400F
- Air flow, max: 100 lbm/second
- Full Bi-directional rotation capability
- 20 to 22 inch diameter face
- Common shaft attachment scheme with W-7 Facility & the 9X15 LSWT

Rig Health Monitoring System:

- 3500 Bentley Nevada rig health system
  - data acquisition/analysis/archival
  - Proximity sensors
  - Accelerometers
  - 100 channel slip ring

Steady State Instrumentation (ESCORT D):

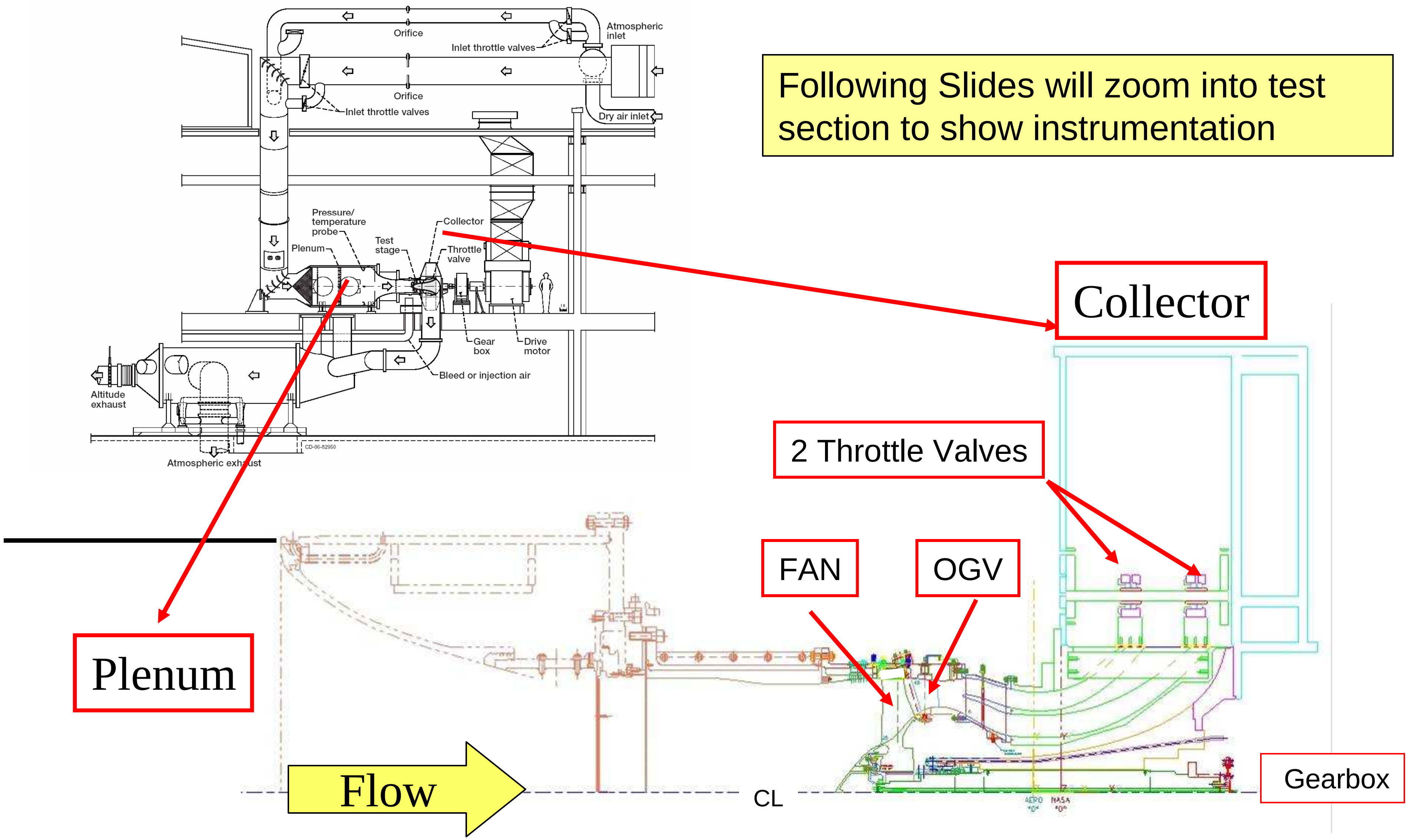
- 256 channels of analog data inputs.
- 320 pressure measurements
- 16 axis probe actuator control system



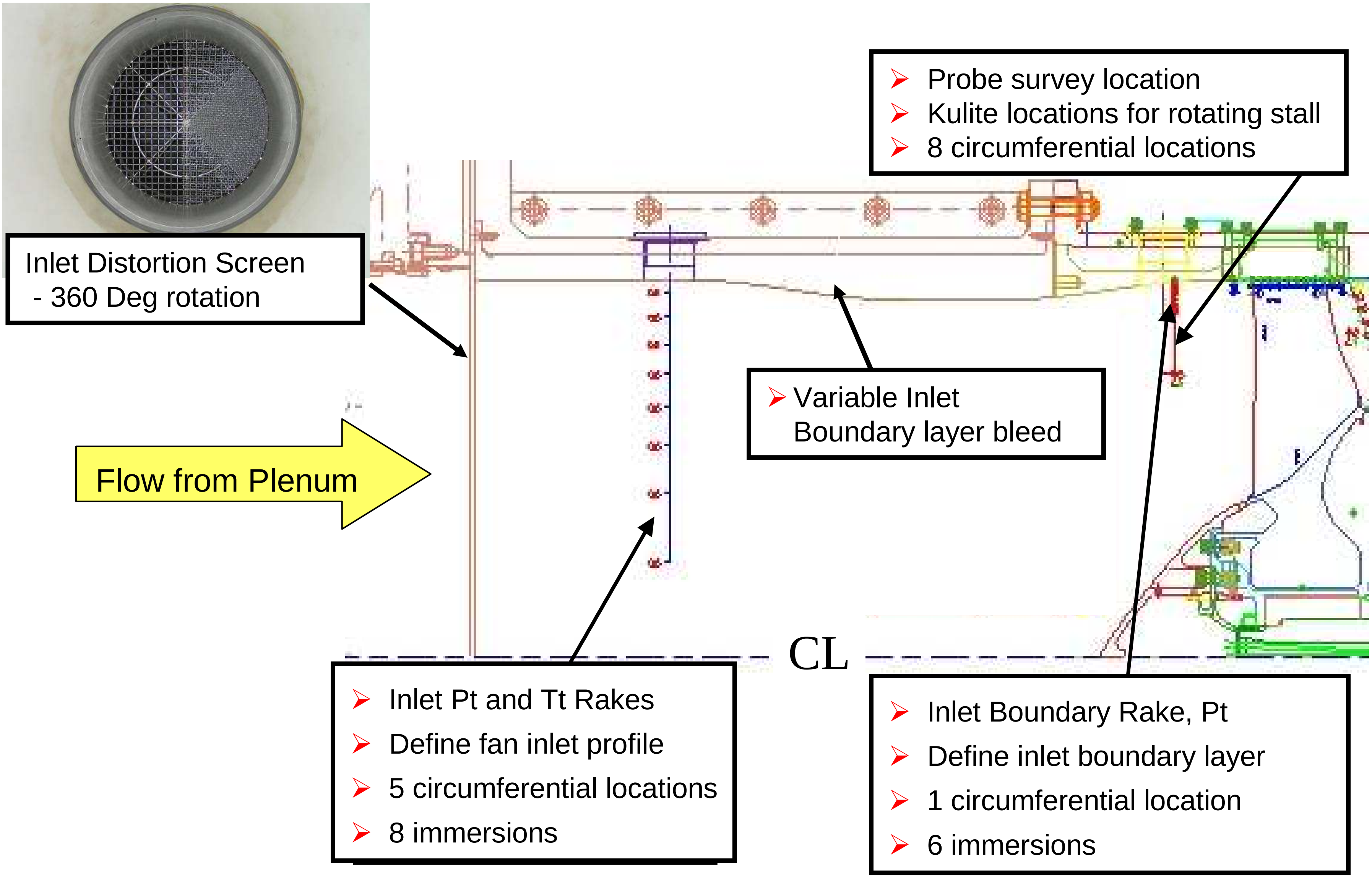
Unique Facility Capabilities Utilized to Obtain Fan Windmilling DATA

Fan Stage Test Section Schematic

Following Slides will zoom into test section to show instrumentation



Instrumentation

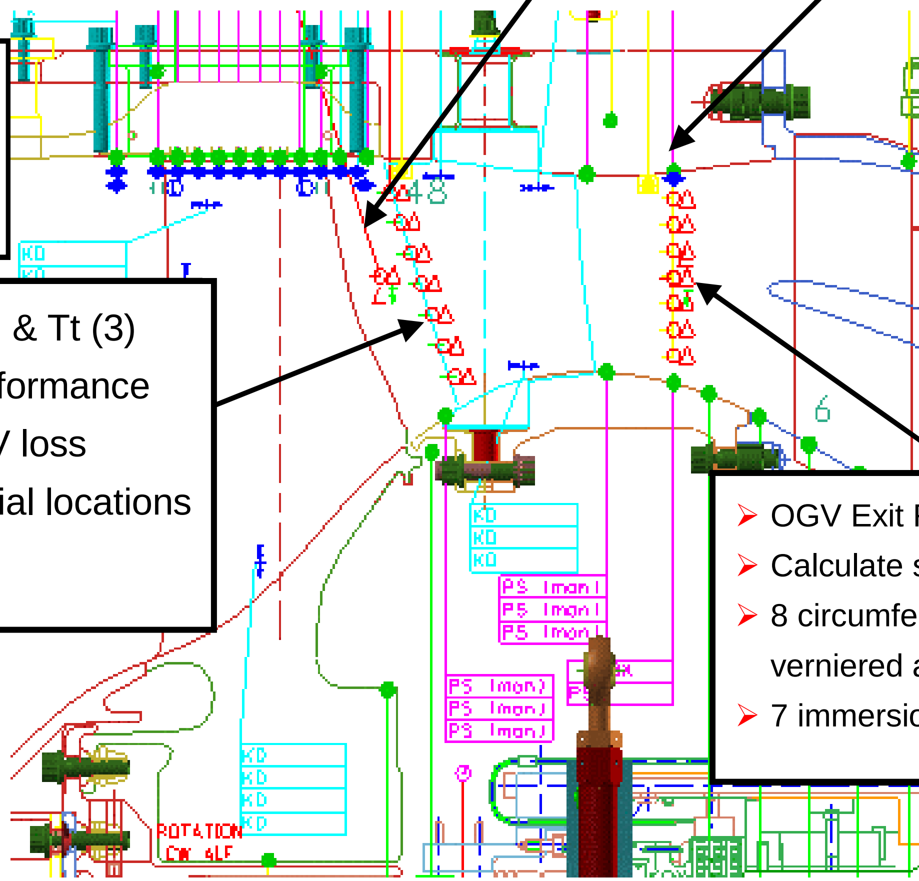


Instrumentation

- Rotor Tip Statics - Steady / Unsteady
- 20 axial locations for each
- Measure rotor endwall shock structure / tip leakage vortex

NASA radial traverse

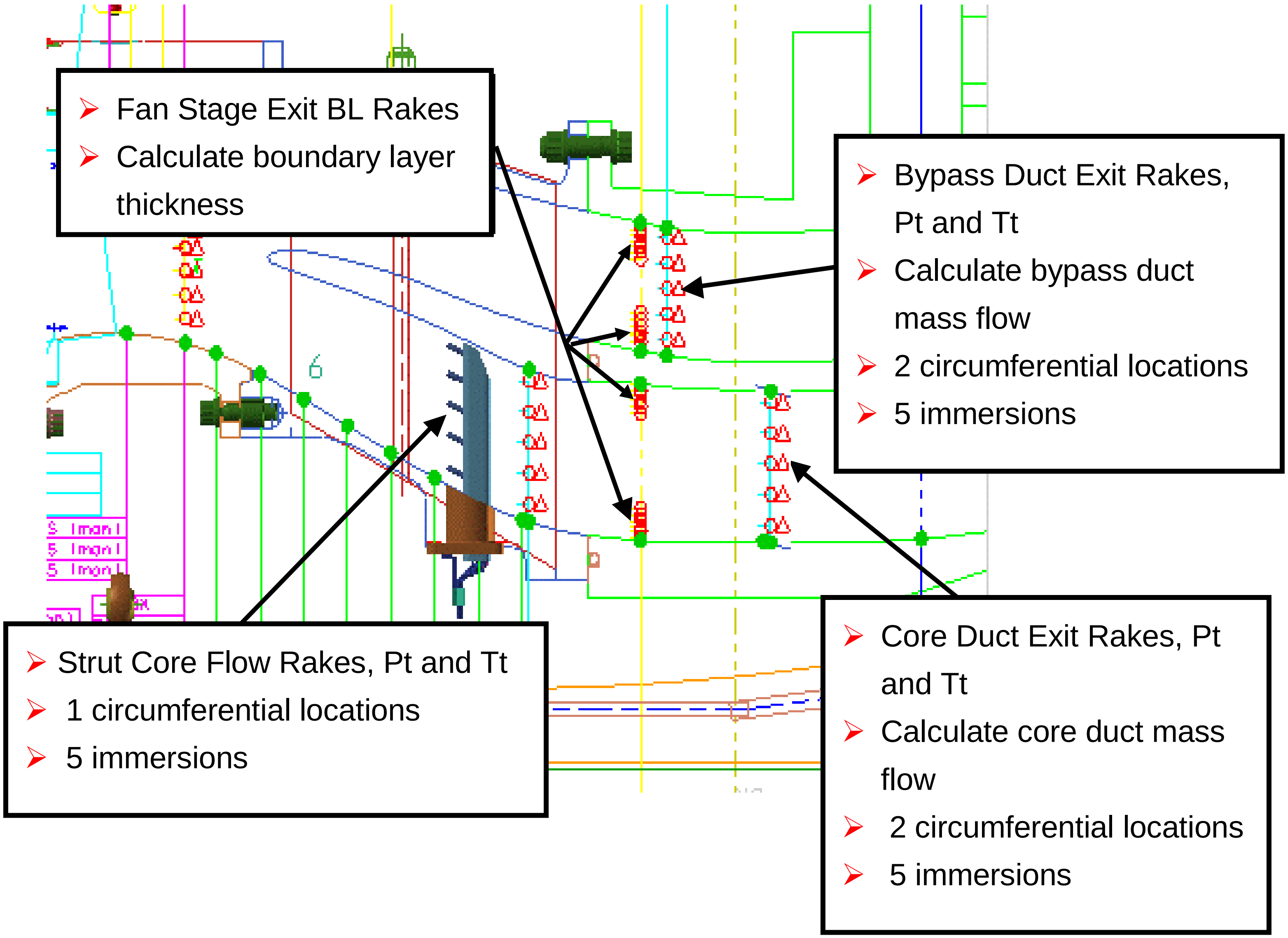
NASA radial & circumferential traverse



- OGV LE Pt (3) & Tt (3)
- Rotor only performance
- Calculate OGV loss
- 6 circumferential locations
- 7 immersions

- OGV Exit Rakes, Pt & Tt
- Calculate stage performance
- 8 circumferential locations, verniered across an OGV passage
- 7 immersions

Instrumentation



TBCC Fan Stage : Aeromechanic Results - Smooth Wall Configuration

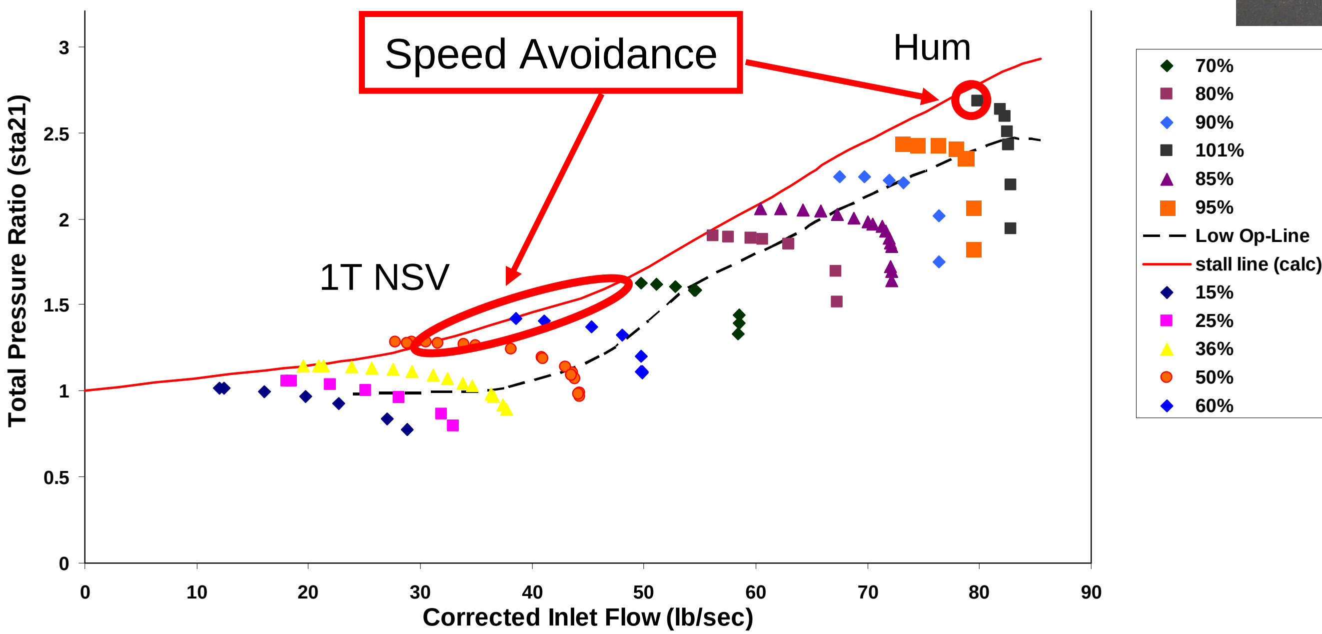
Aeromechanic Instrumentation:

- Dynamic Strain Gages (Rotor :21; OGV: 20; Inlet Rakes :12)
- Light Probes at Rotor Leading Edge (10) & Trailing Edge (10)
- Dynamic Tip Clearance Measurements (4 @ 50% chord)

Aeromechanic Results:

- Speed Avoidance Zones for the Smooth Wall Clean Inlet Flow Condition:
  1. Near Stall from 51-67% Speed due to Non-synchronous vibration /excitation of the Rotor's First Torsion mode (1T NSV)
  2. 100% Speed Near Stall (Hum - not identified)

GE57 fan rig – fan blisk thin-film strain gages



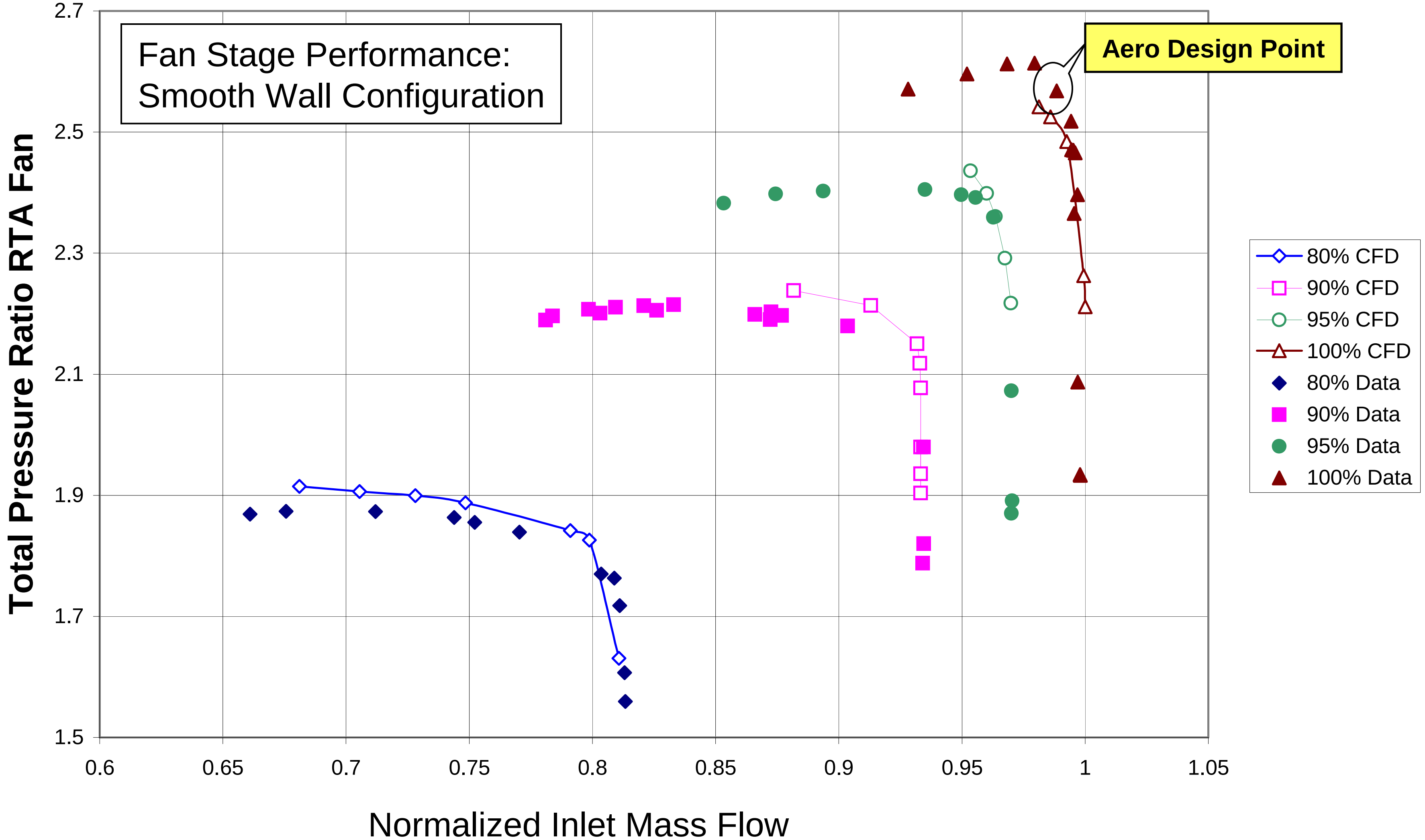
OGV

GE57 fan rig – fan OGV strain gages

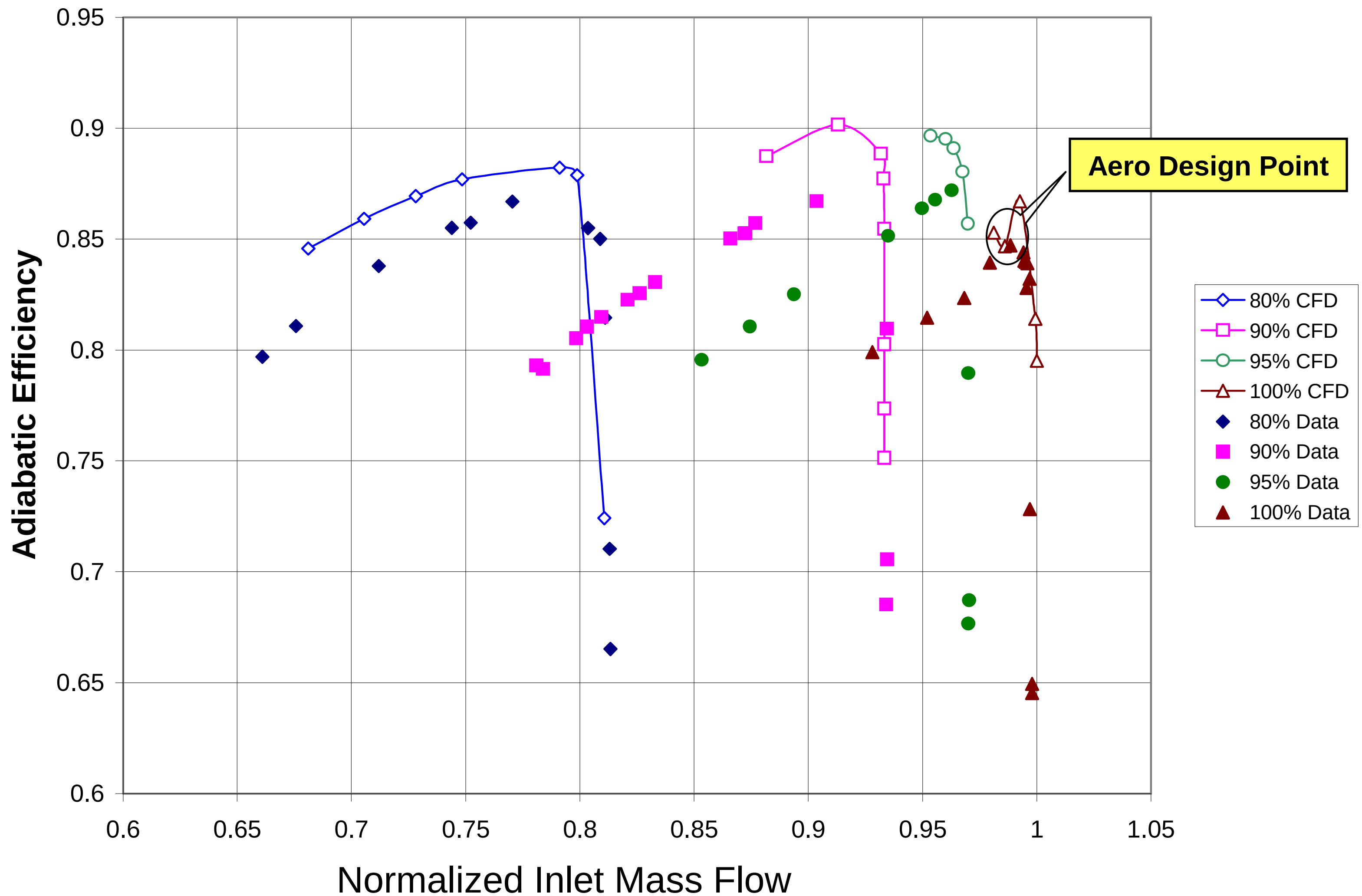
Fan Stage Cleared for 15-100% Speed Operation **Except** at Identified Speed Avoidance Zones

Pre-Test CFD Compared to DATA

Pre-Test CFD does NOT predict Range of Operation @ High Speed



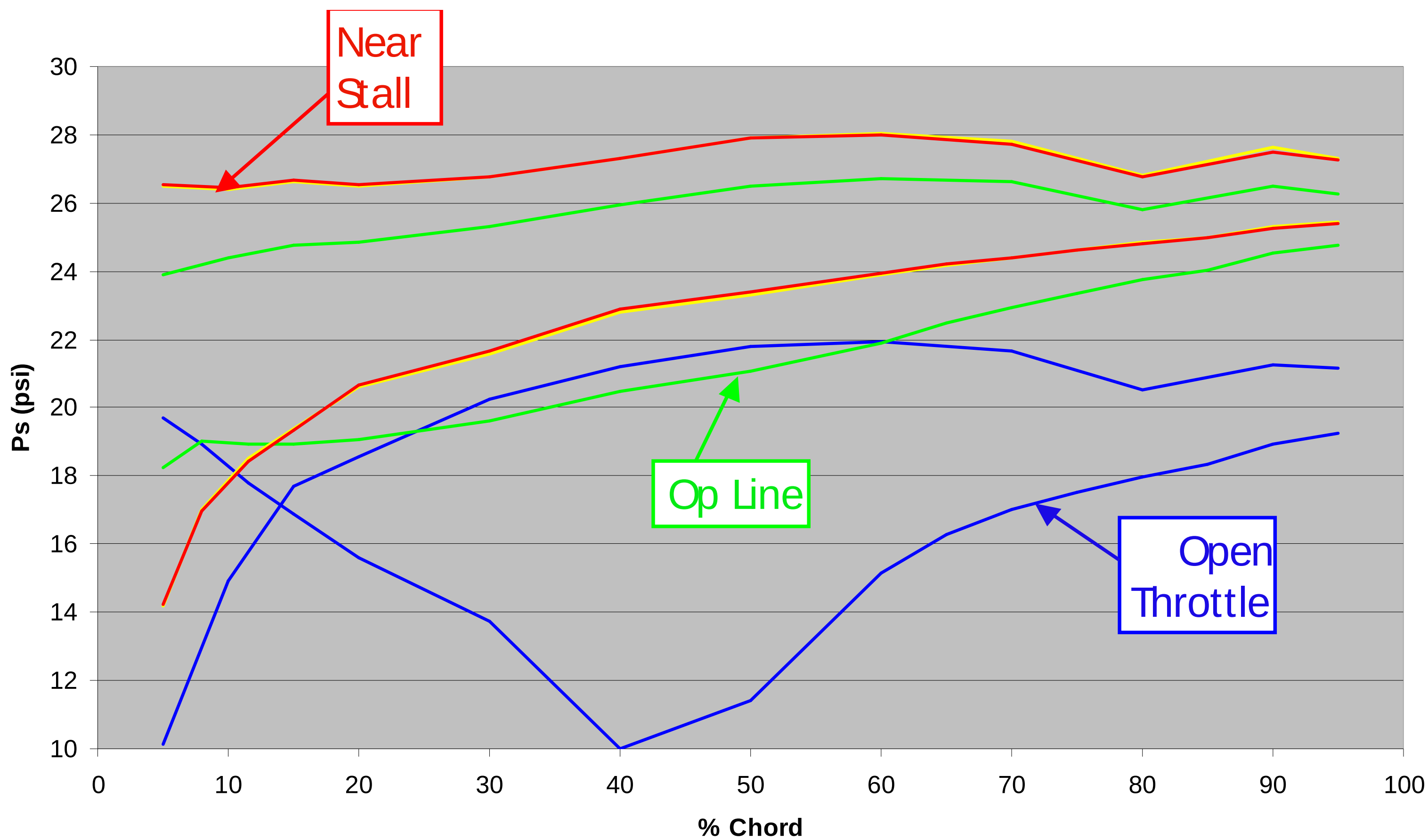
Pre-Test CFD Compared to DATA

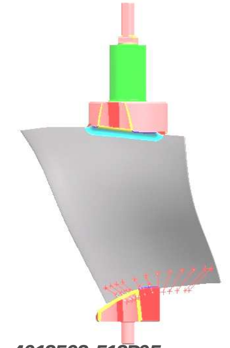


Efficiency Discrepancy Between Pre-Test CFD and Rake Measurements

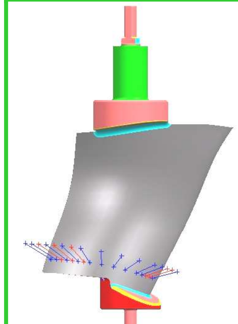
Instrumentation - OGV Blade Surface Static Pressure

OGV pressure and suction surface static measurements at 10%, 15%, 25% and 45% span - Results @ 25%Span, 95% rotor speed.





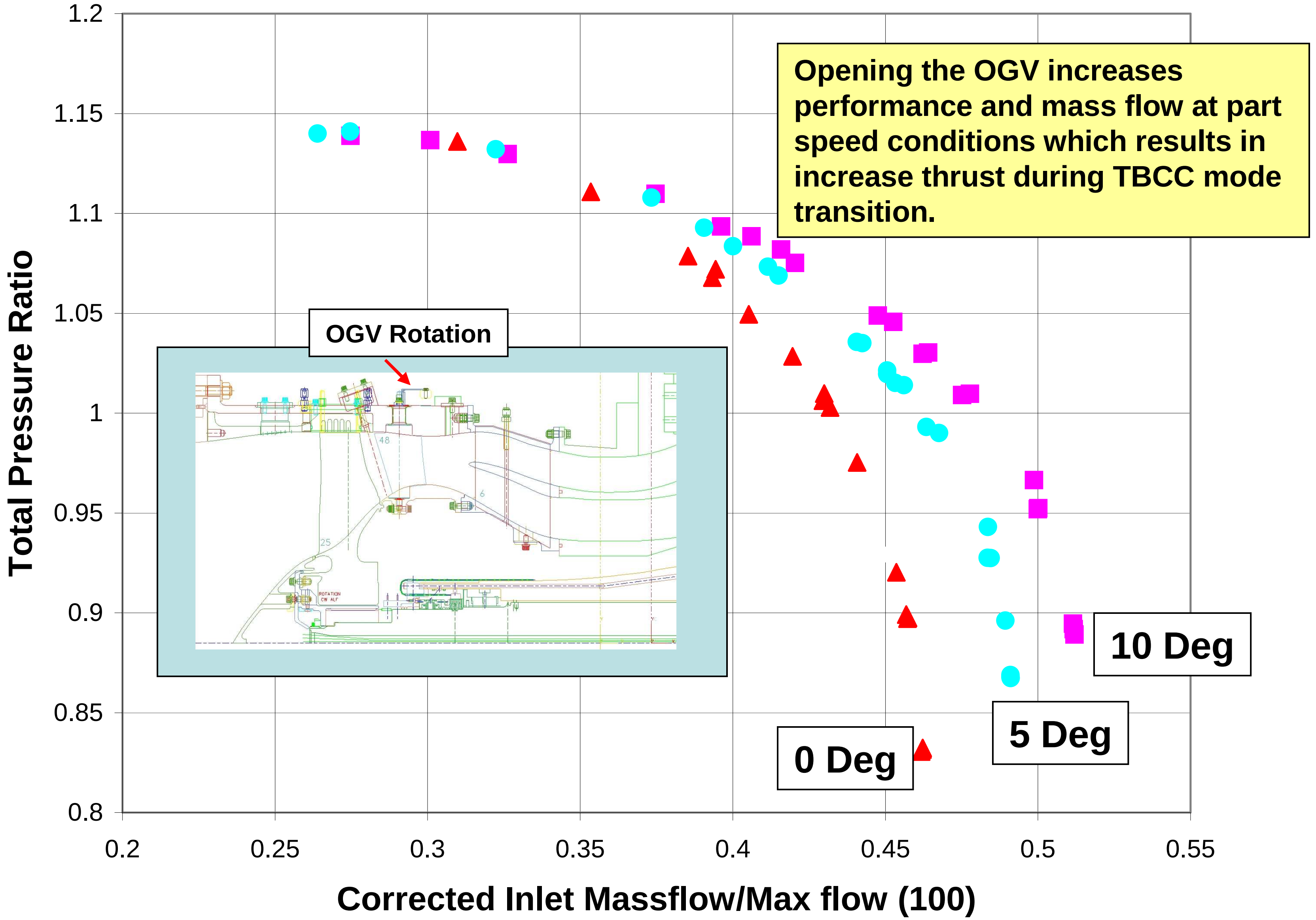
4013562-513P05
OGV, on-airfoil PS
10% span, pressure-side



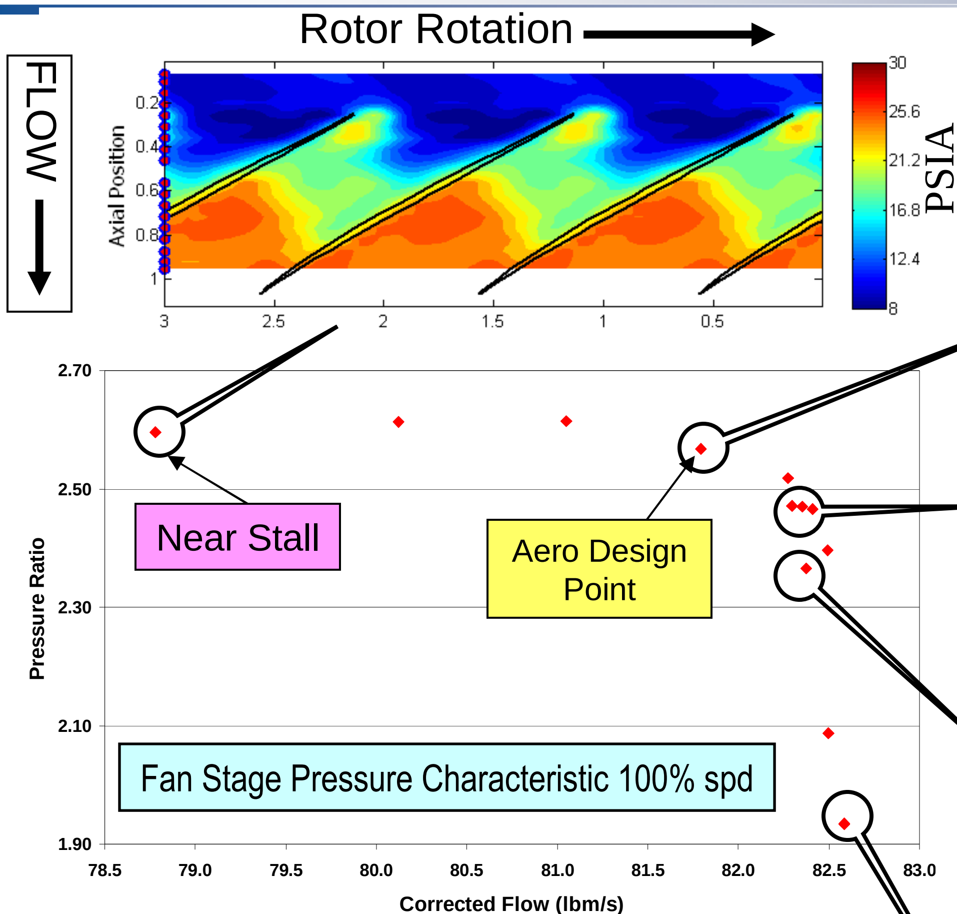
4013562-513P06
OGV, on-airfoil PS
10% span, suction-side

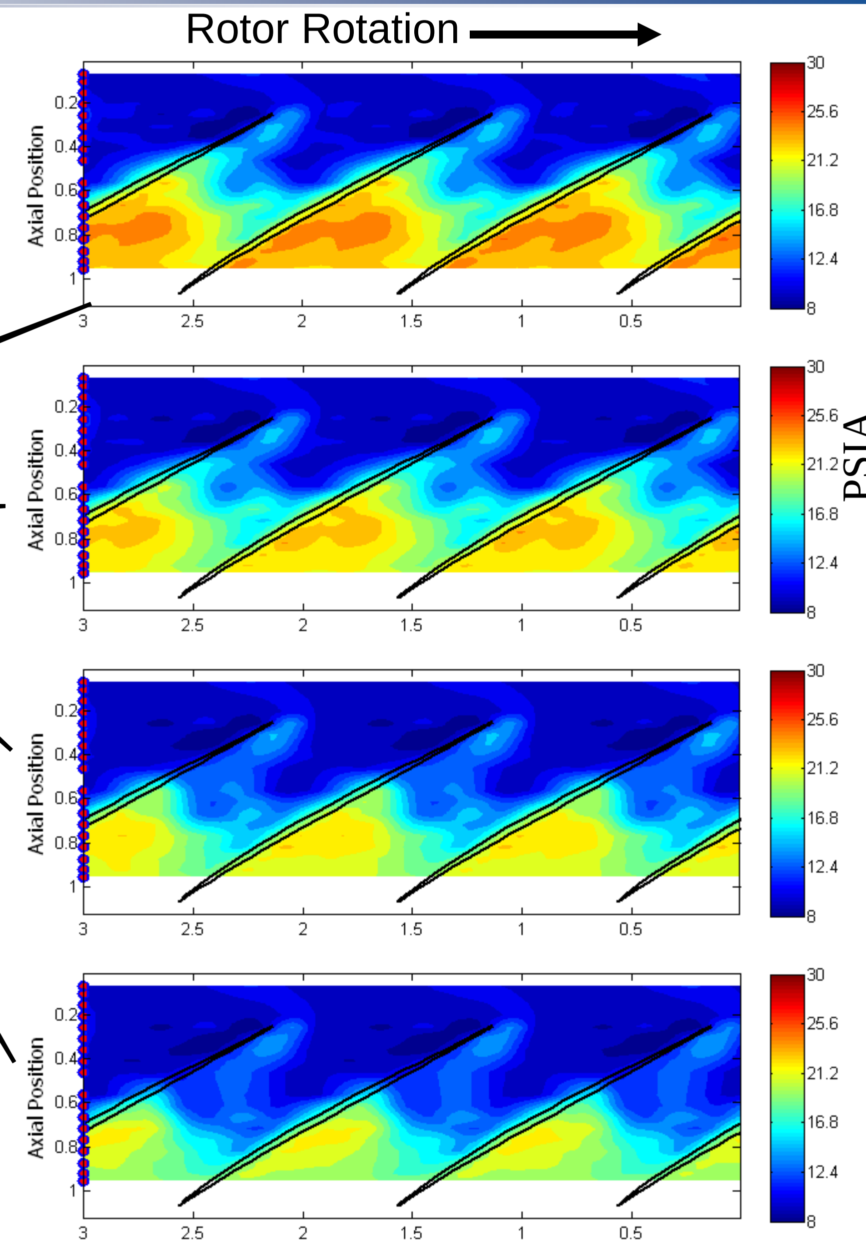
OGV surface statics indicate blade incidence, blade loading,& separations

Sensitivity to OGV Setting Angle : 37% Speed



Rotor Tip Static Pressure Measurements: 100% Speed



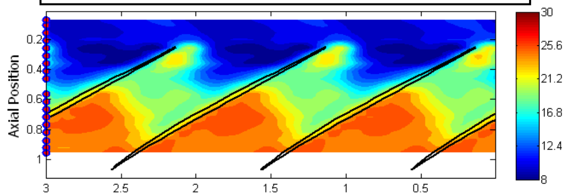


High Response Rotor Tip Static Pressure Measurements (Kulites) Characterize Rotor Endwall Shock / Leakage Vortex Interaction/s.

Concluding Remarks

- A SOA Mach 4 turbine engine fan stage was designed and scaled (0.57 linear) for testing in the NASA W8 high speed compressor facility.
- CFD was utilized in the design process and simulations were performed to predict performance and operability prior to test.
- Aerodynamic fan stage performance characteristics were acquired at 15%, 36%, 50%, 60%, 70%, 80%, 85%, 90%, 95%, and 100% of design rotor speed. Measurements are being compared to Pre-test CFD. Results to date include:
  - *Good agreement at the design point*
  - *Discrepancy in efficiency values over the speed range*
  - *Pre-Test CFD does NOT predict Range of Operation @ High Speed*
- Future Efforts include in depth analysis of CFD and its comparison to measurement, specifically:
  - *Rotor endwall flow structure - using steady and high response pressure measurements.*
  - *OGV blade loading using blade surface static measurements at 10%, 15%, 25% and 45% span.*
  - *Stage performance based on detailed aerodynamic probe surveys (radial and circumferential).*
- Additional fan stage testing to assess sensitivity (both CFD and measurement) of performance and operability to:
  - *Endwall tip clearance*
  - *Endwall flow control including casing treatment*
  - *Inlet flow distortions (radial, circumferential, and TBCC inlet)*

Rotor Endwall Flow Structure



Inlet Distortion Screens